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Comparison of Frequency Conversion Techniques for Magnetoelectric Sensors

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Abstract

Recent advances in magnetoelectric sensor systems prove their growing importance for biomagnetic sensing applications. But with increasing sensitivity down to some pT in mechanical resonance the sensors require techniques to convert low frequent biomagnetic signals in the range of 0.1 Hz to 40 Hz into the mechanical resonance frequency of the cantilevers to utilise the effect amplification of the first bending mode. This contribution introduces the frequency conversion via electrical modulation of the piezoelectric phase and readout via the piezoelectric phase in both basic theory and experiment and compares the results to a magnetic frequency conversion method. The electrical frequency conversion shifts the wanted signal into the mechanical resonance but, with the current setup and sensors, is about a decade less sensitive compared to the magnetic approach. Suitable offsets in the magnetic frequency conversion effectively reduce the noise level by more than two decades.

Keywords: Biomagnetic Sensors; Frequency conversion

1. Introduction

Magnetoelectric (ME) sensors utilise the magnetoelectric effect to produce an output voltage or charge proportional to the applied magnetic field [1]. A magnetostrictive material and a piezoelectric material are coupled mechanically via a carrier material. A magnetic field leads to a variation in length of the magnetostrictive material

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which causes a mechanical stress. This stress is coupled into the piezoelectric phase of the sensor and generates a polarisation change which can then be detected, amplified and processed. The ME sensors used in this work have the shape of a cuboid that is clamped rigidly to a holder on one short side. Their mechanical resonance frequency, the first mechanical bending mode of the cantilever, features an effect amplification for the sensed signal in its bandwidth. Therefore it is suggested to convert low frequency signals such as biomagnetic signals into the mechanical resonance.

Two techniques for low frequency measurements with magnetoelectric sensors have been introduced in [2,3]. With the currently available sensors both methods yield comparable results in terms of readout sensitivity, which at this time is above the required level for biomagnetic signals because the frequency conversion decreases the sensitivity mainly due to conversion loss.

The magnetic frequency conversion (MFC) technique has been designed and implemented with focus on the utilisation of the quadratic region of the magnetostriction curve to maximise the output signal at the mechanical resonance of the magnetoelectric sensor. A drawback of this procedure is additional Barkhausen noise [2,4] which may occur predominantly in the vicinity of the zero crossing of the magnetostriction curve. The usage of higher order Fourier coefficients for example by superposition of an offset to the modulation signal will result in less output signal at the desired frequency because the higher order Fourier coefficients are smaller, but also yield less Barkhausen noise.

2. Sensors and Theory

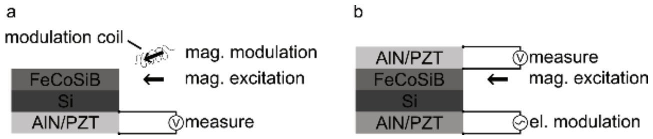

Fig. 1. (a) Magnetic frequency conversion: The desired measurement signal couples into a mechanical mode via the magnetostrictive layer together with an additional modulation signal, which is provided by a current controlled modulation coil. (b) Electric frequency conversion: The magnetoelectric sensor has an additional piezo-electric layer which is used to apply an electric modulation signal.

The sensors used for this investigation mainly consist of iron cobalt, silicon boron (FeCoSiB), aluminium nitride (AlN) or lead zirconate titanate (PZT) and Si in a 2-2 configuration as can be seen in Fig. 1a and Fig. 1b. The cantilevers are 25 mm long and 3 mm wide. Further sensor parameters and details on the production can be found in [5].

For magnetic frequency conversion the modulation signal is generated by a current-fed coil cylindrically wrapped around the cantilever which is superimposed with the magnetic excitation B_{AC} (see Fig. 1a). In the case of electrical modulation the modulation signal is applied to one of the piezoelectric phases as can be seen in Fig. 1b.

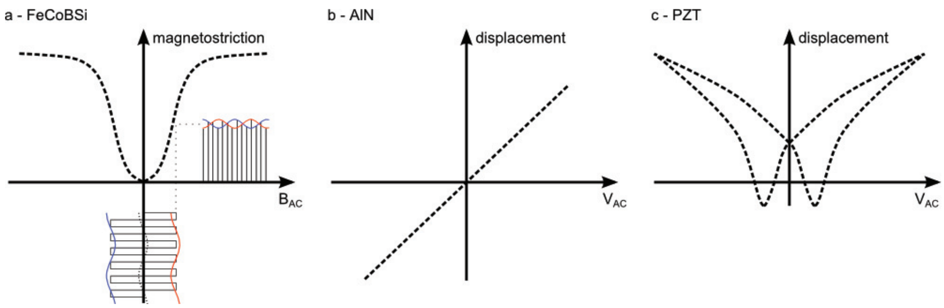

Fig. 2. (a) Theoretical magnetostriction curve of FeCoSiB and indication of an exemplary excitation on the lower part of the y-axis with a rectangularly shaped modulation signal (solid line) superimposed with a low frequency AC measurement signal (dotted line + auxiliary lines in red and blue). The resulting output signal with doubled modulation frequency for an ideal quadratic behaviour is indicated on the right side of the plot. (b) Theoretic displacement curve of AlN. (c) Example of a possible PZT displacement curve [6] with hysteretic behaviour.

The magnetic frequency conversion utilises the nonlinear characteristic of the magnetostriction curve of FeCoSiB to convert the signal into the mechanical resonance frequency [3]. Fig. 2a exemplarily shows the modulation with a rectangularly shaped signal and the resulting output. A rectangular signal could make full use of the steepest slopes of the magnetostriction curve, but unfortunately it is impossible to realise such a field with a coil. To reduce Barkhausen noise an offset can be applied to the waveform to avoid zero crossings in the magnetostriction curve.

For the electrical frequency conversion (EFC) there are almost no restrictions on waveform types. An electric voltage signal is applied to the piezoelectric phase which causes a strain modulation in the material. Fig. 2b and 2c indicate the relationship between applied voltage and displacement for two piezoelectric materials. Because the magnetostrictive material is mechanically coupled its magnetization changes as a function of the strain (magnetoelastic effect). If for AlN the frequency of the driving voltage is chosen to be $f_{res} - f_s$ the wanted magnetic signal at f_s is converted into the mechanical resonance of the cantilever. However, the conversion process is very different from the MFC. Only tensile stress produces a large change of magnetization, compressive stress has nearly no effect. Therefore the magnetostriction curve (see Fig. 2a) is run through only every half period. Thus the output signal depends even more on the magnetic history, e.g. a magnetic bias resulting from exchange bias. In the case of PZT the strain modulation is more complex because the transfer function is not linear (see Fig. 2c).

Frequency conversion is always accompanied by a conversion loss and thus converted signals yield a sensitivity worse than if the same signal was measured with an excitation in resonance.

3. Experimental and results

The signal from the sensor is preprocessed with a low noise charge amplifier and then read out either via a lock-in amplifier SR830 or a spectrum analyzer SR785. The modulation signal is generated by the internal source of the spectrum analyzer and in case of the magnetic modulation a voltage controlled current source. The signal to be measured B_{AC} is generated by a Keithley 6221 precision current source and a coil. All measurements are conducted in an acoustically, electrically and magnetically shielded box (see [7] for further details).

To determine the optimal modulation current or voltage the amplitude and the SNR of the frequency shifted signal (the upper sideband) is monitored while the modulation amplitude is swept until a maximum is reached. This current or voltage (optimal amplitude) is then used to perform the frequency conversion which shifts a signal with $f_s = 10$ Hz into the mechanical resonance of the cantilever.

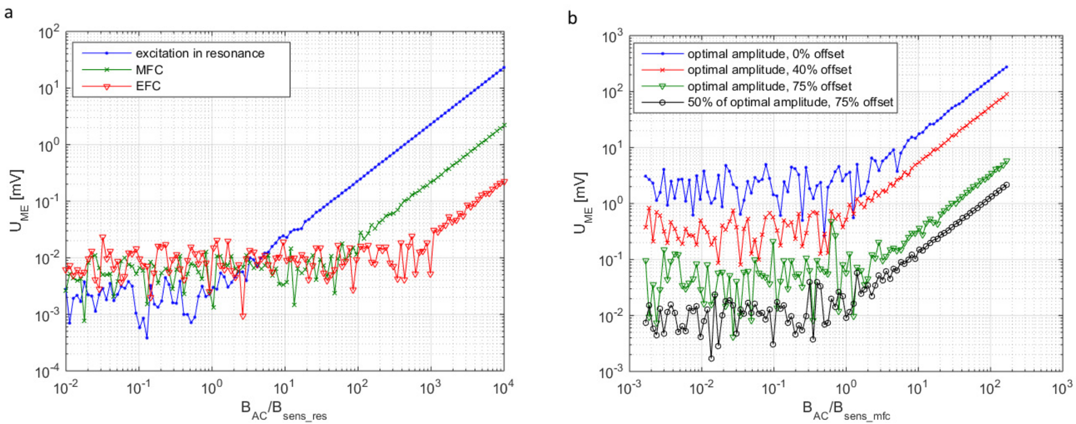

Fig. 3. (a) Comparison of frequency conversion techniques in noise level, linearity and level of detection (LOD) for an AlN-FeCoSiB-Si-AlN sensor. The flux densities are normalized to the LOD in resonance to emphasise the discrepancies. (b) Magnetic frequency conversion of a PZT-Si-FeCoSiB cantilever with different coil driving currents. The offsets are given as a percentage of the optimal amplitude.

Fig. 3a shows linearity measurements at the mechanical resonance at $f_{res} = 861$ Hz of the cantilever for an AlN-FeCoSiB-Si-AlN sensor using three different methods normalized to the level of detection in resonance. For reference the direct excitation in resonance is depicted (B_{AC} is applied directly at resonance). For the frequency conversion techniques the B_{AC} is now applied with $f_s = 10$ Hz and consequently converted into the mechanical resonance. For the MFC the noise level at f_{res} rises approximately by a factor of three, but the LOD is worse by 1.5

decades. This is due to conversion loss and additional Barkhausen noise occurring mainly at the zero crossing of the magnetostriction curve (see Fig. 2a). The noise level of the EFC at f_{res} is approximately five times higher than with excitation in resonance and the LOD is worse by 2.5 decades. Additional noise of the piezoelectric layer used for excitation is converted into the mechanical resonance and thus contributes to the overall noise at the output. Also, as mentioned in Sec. 2, the magnetization due to the magnetoelastic effect does not change continuously which reduces the conversion effect.

Fig. 3b shows the linearity measurements with MFC of a PZT-Si-FeCoSiB cantilever with coil driving currents of different amplitudes and offsets. The blue curve is measured with the optimal modulation amplitude but without offset and features the highest mean noise level of approximately 2.23 mV. Increasing the offset lowers the noise level (red and the green curve). It also reduces the signal level and the slope of the linearity curve. Choosing a modulation amplitude less than the offset lowers the mean noise level to around 0.01 mV. With this configuration no zero crossings occur and thus Barkhausen noise is minimized while the signal level decreases further. As mentioned in the introduction an offset drives the magnetostriction curve into non-quadratic regions which lessens the signal energy converted into $f_{mod} + f_{res}$. The relation between signal level and noise stays approximately the same since the LODs do not change significantly as can be seen in Fig. 3b.

Using the AlN layer for excitation different waveforms do not have a significant effect on the output signal or the output noise level. The gradient of its linear characteristic does not change therefore the operating point on the displacement curve is not essential. Also the mechanical movement of the cantilever has a certain inertia mainly due to the thick layer of silicon which low pass filters or smoothens waveforms.

4. Conclusion and outlook

Two methods for frequency conversion have been investigated, implemented and compared with respect to a direct excitation at the mechanical resonance of a cantilever. The measurements demonstrated that with optimization of the output SNR by variation of the modulation signal the LOD of the MFC is approximately one decade lower compared to the EFC and that both methods introduce additional noise sources as well as an intrinsic degradation of the signals due to conversion loss. By applying an offset in order to avoid zero crossings the noise level of the MFC decreased by more than two decades, but due to non-quadratic behaviour of the magnetostriction curve the signal level at the output decreased almost equally.

Further optimization can be achieved in the sensor design e.g. by adequately shifting the magnetostriction curve via exchange bias to address specific coefficients of the curve and to magnetise the magnetostrictive layer without interruption. Different waveforms and offsets can be applied to a PZT layer to make use of its nonlinear displacement characteristic.

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